Chapter 5

Burners and Flames

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D. Pauling
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Introduction

The function of the burner is to introduce the fuel into the burning zone.

The propagation of the combustion process depends on how fast the combustible comes into contact with oxygen. It is therefore the essential function of the burner to regulate this mixing process adequately in order to achieve a correct flame shape.

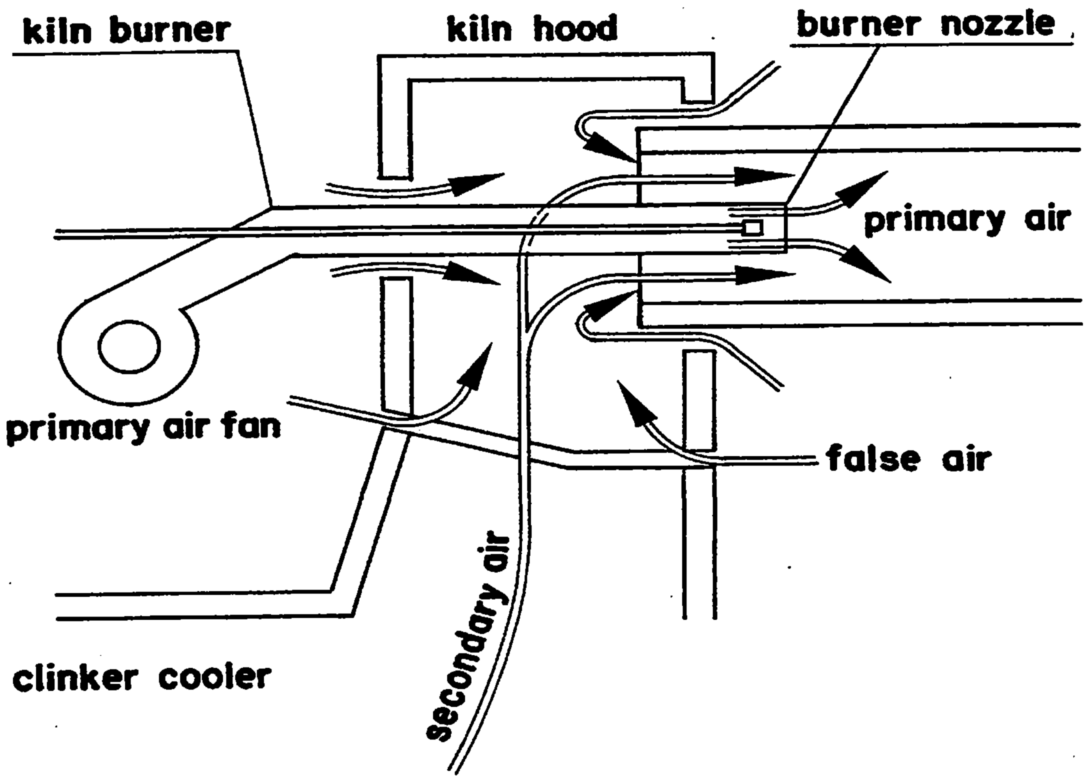
This process must take place in such a fashion that the heat is released at exactly the right place without producing any damaging effects and without producing excessive pollutant elements such as NOx, SOx and CO. Consequently, any optimization of the burning process must start with the correct adjustment of the flame.

This paper describes how the flame can be adjusted, what burner types are available and under what conditions they work best.

1. TERMINOLOGY

- Primary air + secondary air + false air = combustion air
- Stoichiometric combustion air + excess air = combustion air

Figure 1: Terminology of Combustion Air



2. BURNERS

2.1 Mono Channel - / Straight Burners

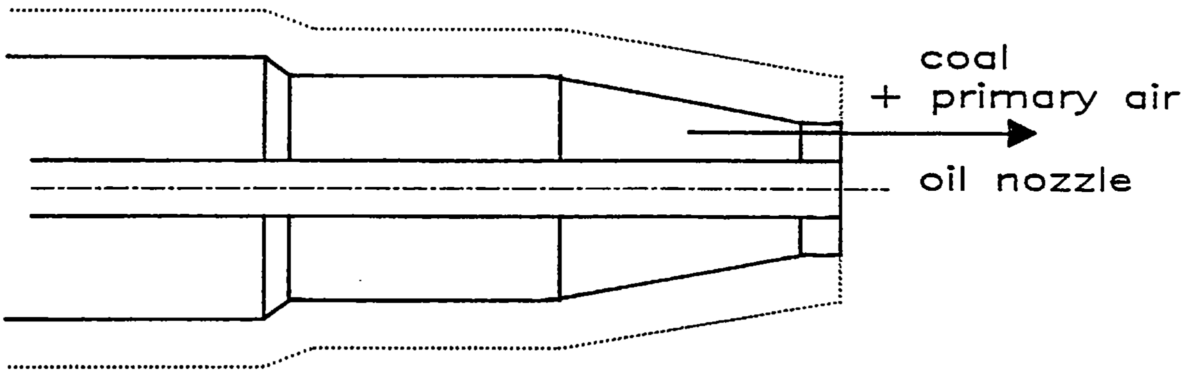
2.1.1 Burner Design

The mono channel burner is the most simple burner design. With this burner type, coal dust and all the primary air is injected together through a single tube. Usually this type is used for long kilns, equipped with direct firing.

Mono channel / straight burners can also be used for fuel oil firing or for a combination of coal and oil firing (additional channel for the oil nozzle in the center).

Conical burner tips can be used to increase the injection velocity (Fig. 2).

Figure 2: Straight Burner



2.1.2 Burner Characterization

A high axial impulsion (massflow of fuel and primary air multiplied with the injection velocity) leads to an intense mixing of the combustion air with the fuel. This intensive mixing has two effects:

1) strong and stable flame; good (complete) combustion
2) high NOx formation

Recommended range of specific axial impulsion (Gax) for mono channel burners:

$$Gax = \frac{M_{(\text{transport air+fuel})} \cdot V_{\text{transport air}}}{Q_{\text{fuel}}} = 6 - 7 \frac{N}{MW}$$

M: Massflow Transport Air + Fuel (kg/s)

V: Injection Velocity (m/s)

Q: Fuel Input (calorific value · fuel massflow) $\left[\frac{MJ}{kg} \cdot \frac{kg}{s}\right] = [MW]$

This corresponds with the old rule of thumb, which states that the kinetic energy of the primary air jet of a mono channel burner should be kept constant within certain limits:

$$\boxed{(\text{Velocity of Primary Air})^2 \quad (\%\text{Primary Air}) \quad = \quad 65'000 \quad - \quad 75'000}$$

Even if this formula will not give optimal values in each case, it enables a rough estimate of the dimension of the burner if presupposed as a second condition that the primary air jet velocity should lie between 50 and 100 m/sec (valid for straight burners without swirl).

2.2 Multi Channel Burners

2.2.1 Burner Types

The most simple design of a burner is the mono channel burner (see Chap. 2.1). However, for optimum flame shaping when considering changing coal quality and different requirements from the point of view of raw mix burnability, burners with adjustable flame are to be preferred. In such burners, the primary air is usually divided into an axial and a radial component with the coal also introduced via a concentric ring tube.

These burners are called multi channel burners, and are usually suitable for alternate or combined firing of coal, oil or gas. The axial air is injected in the direction of the kiln axis (similar to a mono channel burner where all the air is injected in axial direction).

The radial air or swirl air is injected with a direction towards the kiln wall.

The swirl component of the radial air creates a rotating air flow along the kiln axis (similar to the threat of a screw). This airflow is also pushing towards the outside, in direction of the kiln wall.

Since the radial air channel is located inside the axial air channel (both are concentric ring channels), the radial air is opening up / widening the flow of the axial air.

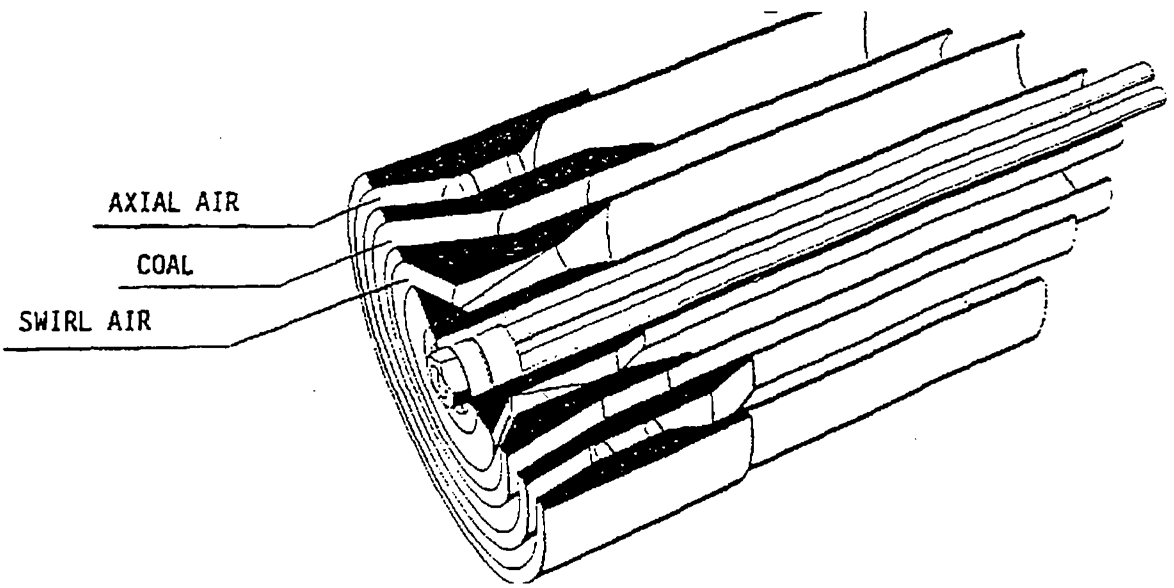
An increase of radial air versus axial air therefore creates a wider and shorter flame. An increase of axial air versus radial air create a longer flame.

Besides flame shaping, the primary air also has to keep the burner pipe cool.

A typical example of the first generation of multi channel burners is the Pillard 3-Channel Burner (Fig. 3). This burner has the coal channel in between the axial- and the radial air channel. A problem recognized with these burner types is that a shortening of the flame tends to produce a too wide flame (flame impeigements on the kiln wall).

Furthermore coarse cool particles (residue on 200 µm sieve) can be thrown out of the primary air jet by the radial air. These particles can cause reducing condition on the clinker bed and high NOx formation.

Figure 3: Conventional 3-Channel Burner (Pillard)

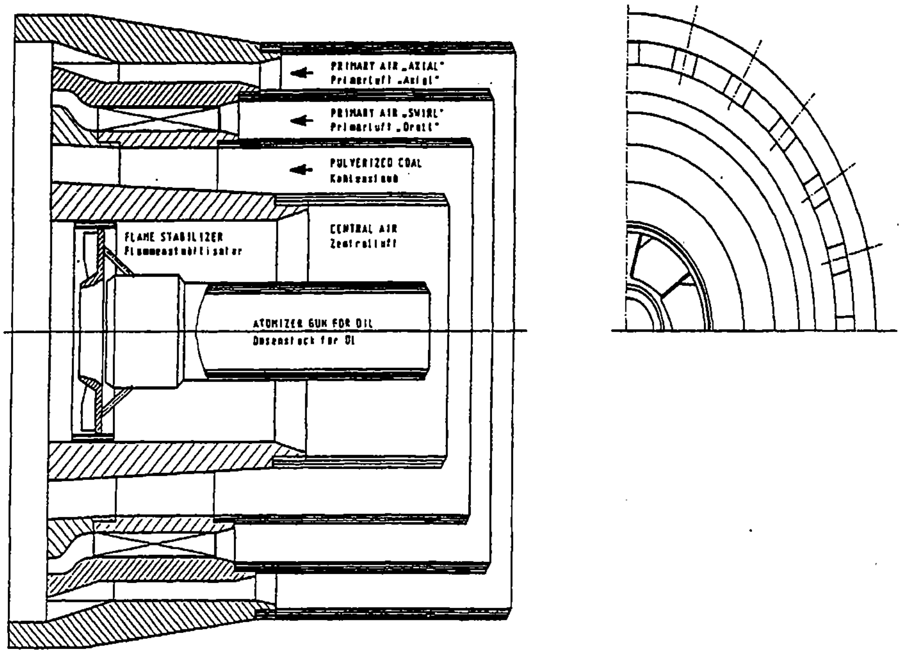


A new generation of multi channel burners has therefore been designed. With special arrangements and constructions of the primary air channels the above mentioned negative effects can be avoided through the creation of a longer and more homogenious internal recirculation zone in the flame (see chapter 3.2.2).

The leading burners of this generation are the Pillard Rotaflam and the KHD Pyrojet.

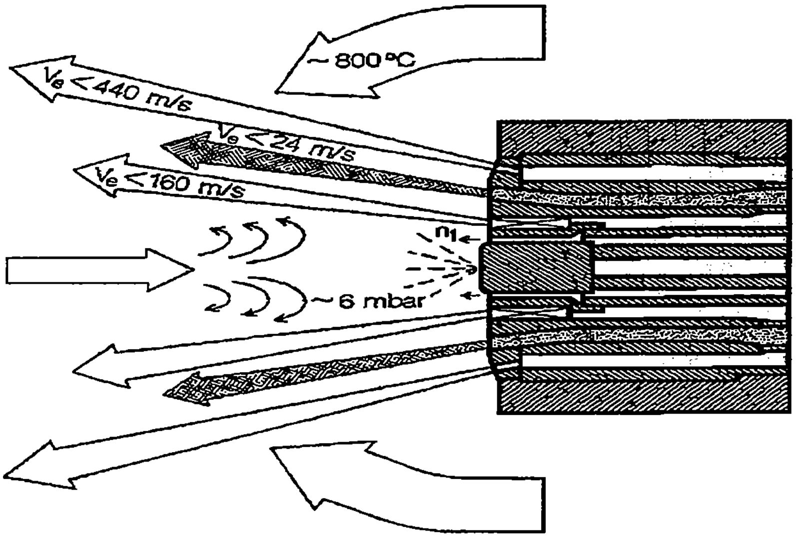
The particular features of the Pillard Rotaflam Burner (Fig. 4) are the location of the coal channel inside the axial and radial air channels, as well as the flame holder / flame stabilizer (bluff-body-effect) in the enlarged center cross section.

Figure 4: Pillard Rotaflam Burner



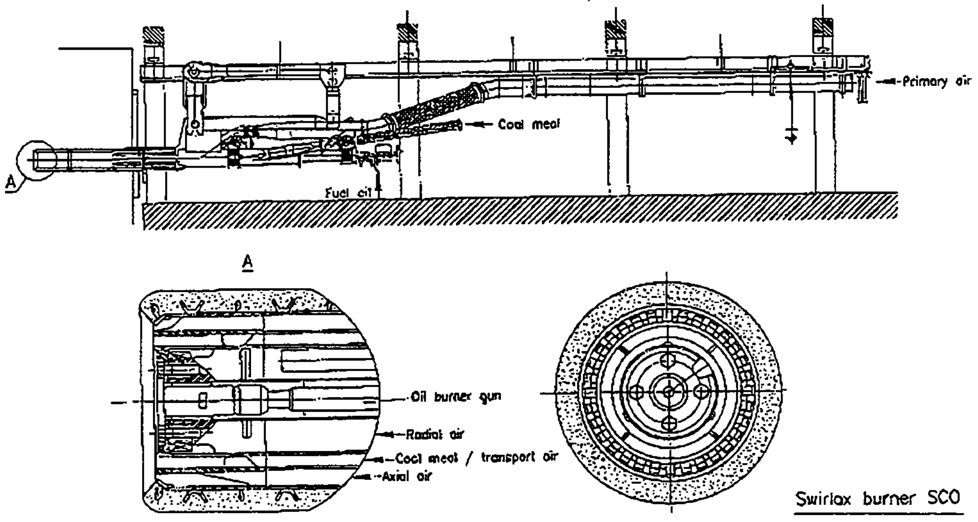
The particular feature of the KHD Pyrojet Burner (Fig. 5) is the jet air. The effect of this burner can be explained by the better and more uniform mixing of fuel and secondary air due to the jet air being introduced at nearly sonic velocity. For this reason the Pyrojet requires a compressor for the jet air.

Figure 5: KHD Pyrojet Burner



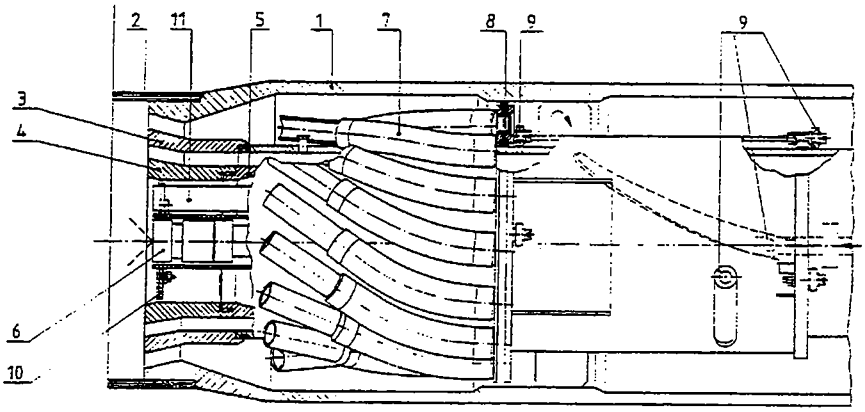
The FLS Swirlax Burner (Fig. 6) applies Pyrojet technology with a license from KHD. The experience in the Holderbank Group is limited.

Figure. 6: FLS Swirlax Burner



Unitherm offers an interesting solution with their M.A.S. Burner (Fig. 7), featuring only one primary air channel with adjustable swirl. However, so far with no application within the Holderbank Group.

Figure 7: Unitherm M.A.S. Burner



2.2.2 <u>Burner Design Recommendations</u>

(Calculation of Gax and S_b : see Annex)

- Specific Axial Impulsion: Gax = 3 - 7

  low volatile coal (10% volatiles): Gax = 7

  high volatile coal (35% volatiles): Gax = 3

  The axial impulsion affects the overall entrainment into the flame. In general a higher axial impulsion results in enhanced mixing and higher NOx emission levels.

- **Swirl Number:** **Normal Range:** **$S_b = 0.1 - 0.25$**

  Maximum Range: **$S_b = 0.4$**

In general higher tangential momentum (expressed through the swirl number) results in a more rapid heat release in the near burner zone and higher NOx emission levels.

◆ **Primary Air Ratio: 10 - 12%**

Experience with these new generation (low primary air) burners has shown, that primary air ratios of 6 - 8% are on the technical limit below which it is no longer possible to guarantee stable combustion conditions.

With primary air ratios of 6 - 8%, any disturbance of the burning process tends to shift combustion to the back kiln zone, producing high kiln inlet temperatures and poor clinker quality (underburning). Therefore in designing the primary air content for modern burners, a minimum of 10% is recommended (including transport air in coal fired systems).

Seen from a heat saving point of view the primary air ratio should be as low as possible in order to recuperate as much hot secondary air as possible. On the other hand, the kinetic energy of the fuel air mixture must be sufficiently high to provide a good mixture with the secondary air to ensure rapid burning.

- Axial air velocity (injection): 100 - 190 m/s (Pyrojet: 300 m/s)
- Radial air velocity (injection): 100 - 190 m/s
- Pressure of radial and axial air: 150 - 200 mbar (Pyrojet axial air: 0.5 - 1 bar)
- Transport air coal (injection): 20 - 30 m/s

[illegible] 25 m/s

2.3 Fuel Oil Atomizers

Once properly prepared in terms of filtering, heating up and delivering to the burner with constant pressure and viscosity, the fuel oil must be atomized for effective mixing with the combustion air. Therefore fuel oil atomizing nozzles are used. These nozzles are located in the center of the burner, surrounded by the injection of the primary air. The oil nozzle is held in place by a jacked tube which is a fixed part of the burner. Thus the atomizing nozzle is retractable, which is necessary to change the orifice plate when increasing the throughput (only mechanical atomizers with fixed orifice - see below) or to take out the oil nozzle whenever it is not needed (e.g. switching to coal firing) to prevent overheating or coking of the unused atomizer.

For fuel oil atomization different principles are employed:

- Mechanical atomization with fixed orifice and variable pressure
- Mechanical atomization with variable orifice and constant pressure
- Assisted atomization with steam or compressed air

2.3.1 Mechanical Atomizers with Fixed Orifice and Variable Pressure

This type of atomization is the most common. Hereby the oil throughput is governed by the pressure of the fuel oil (within the range given by the selected discharge opening/orifice plate).

With these atomizers the fuel oil flow in the atomizer head is often subdivided into an axial and a radial component. By adjusting the pressure and thus the ratio of these components, it is possible to alter the spray angle of the fuel jet. In general, an increase of the radial/tangential oil pressure leads to intensified swirling of radial and axial oil which has the tendency to shorten the flame. Typically the differential pressure is in the range of 1.5 bar (tangential minus axial oil pressure) with an overall pressure of approx. 40 bar. Since the reading accuracy of such small values, compared to the operating range of 40 bars, is unsatisfactory, it is suggested to equip both, radial and axial oil flow with oil flow measuring devices and optimize on flow basis using the flow-pressure curve of the nozzle supplier or to install a separate measurement of the pressure difference between radial and axial oil pressure. Flame shape control is, however, not only a result of atomizer adjustments, but also a function of primary air control.

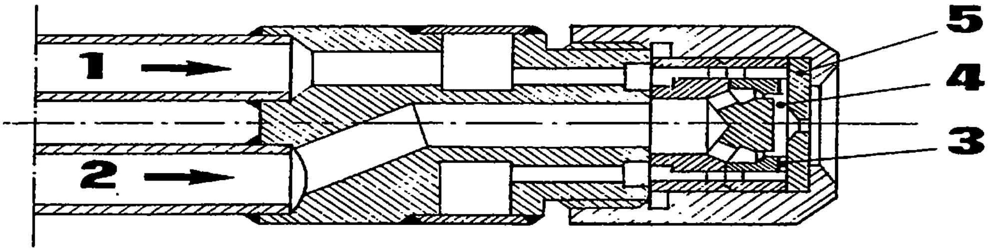
Fig. 8 and 9 show two current atomizers (Pillard and Unitherm) with radial-axial flow or alternatively return-flow for start-up operation. For return-flow, the axial oil flow is used to return a portion of the radial oil flow to the storage tank, in order to have a high flow velocity and oil pressure in the nozzle head (swirl chamber) despite the small amount of oil injected in the kiln (start up phase). Thus the turndown ratio can be increased, still with a good atomization.

Atomizer turndown ratios of 10 to 1 are often given by the suppliers. Practical turn down ratios (without changing the orifice plate) however, are limited to values below 5 to 1 (even for return flow operation during start up).

As an additional feature, the length of the swirl chamber in the Unitherm atomizer is adjustable.

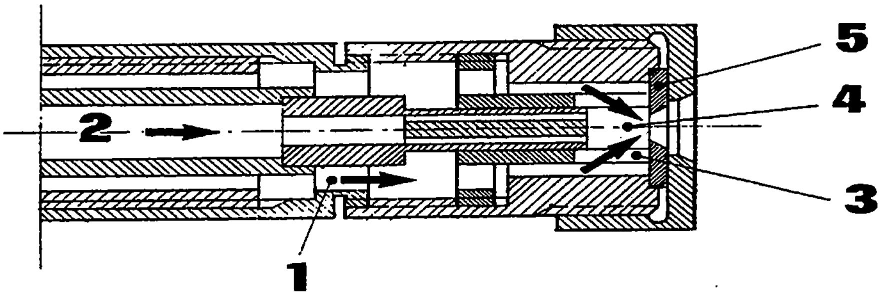
Fig. 10 (Coen Tri-Tip Nozzle) shows a mechanical atomizer with fixed orifice without radial-axial oil flow division.

Figure 8: **Pillard MY Atomizer**



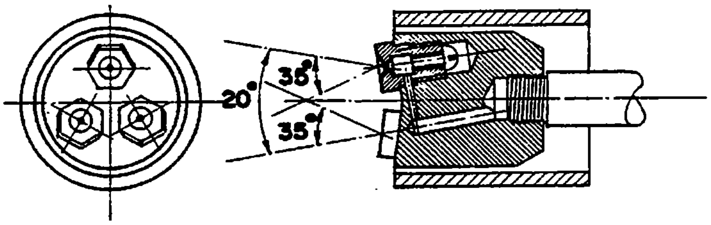
1 tangential oil flow
2 axial oil flow
3 tangential slots
4 swirl chamber
5 orifice plate

Figure 9: Unitherm Atomizer



1	tangential oil flow
2	axial oil flow
3	tangential slots
4	swirl chamber
5	orifice plate

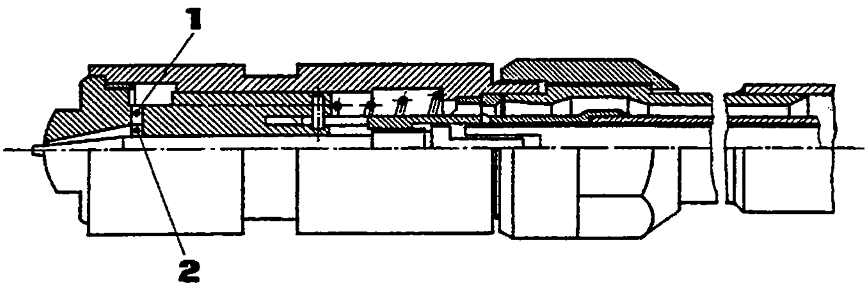
Figure 10: Coen Tri-Tip Nozzle



2.3.2 Mechanical Atomizers with Variable Orifice and Constant Pressure

This type of atomizer employs the adjustable needle valve principle for throughput control. By moving the needle position, contrary to the above described types, the orifice can be adjusted. Atomizing pressures are in the range of 20 bar. The turndown ratio are also limited. Needle value atomizers are mainly used by FLS for long wet kilns (see Fig. 11). Flame shaping is accomplished by adjusting the needle position, oil pressure and primary air.

Figure 11: FLS Atomizer (Needle Valve Principe)

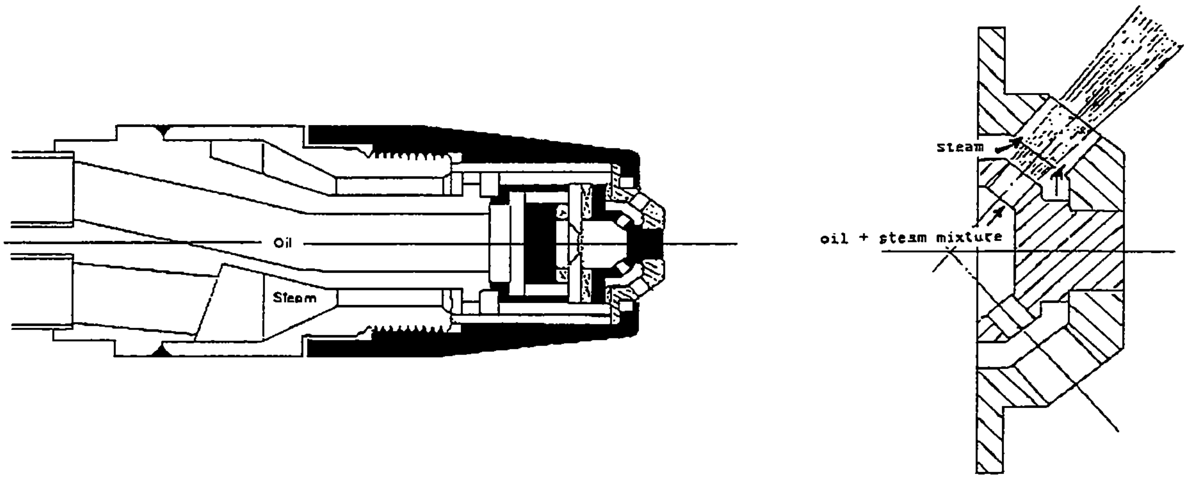


1) tangential slots
2) swirl chamber

2.3.3 Nozzles with Assisted Atomization through Steam or Compressed Air

This type of atomizer (Fig. 12) uses steam or compressed air instead of radial oil to create an intense swirl in front of the orifice plate. The advantage of these atomizers is the higher turndown ratio because even a small amount of oil can be atomized effectively with steam or compressed air. The disadvantage of these atomizers is the need for a significant amount of steam or compressed air, which cost money to produce.

Figure 12: Pillard Atomizer with Assisted Atomization



2.4 Natural Gas Burners

In most modern gas burners the gas flow divided is into radial and axial gas. Primary air is not necessarily needed. However most burners use primary air for flame shaping and burner cooling.

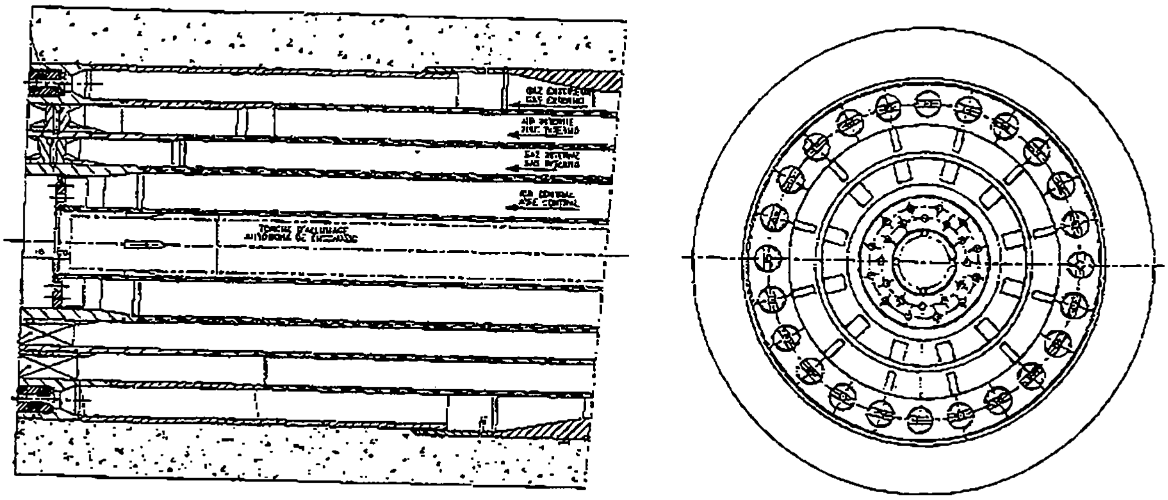
Pillard Rotagas Burner (Fig. 13)

The Rotagas burner is the most recent development from Pillard. The burner is designed for 100% gas firing. Compared with the conventional Pillard Gas Rotaflam, the possibilities to adjust the flameshape have been ameliorated.

Arrangement of the channels (from outside to the center):

- exterior, high pressure gas channel
- radial swirl air channel
- interior, low pressure gas channel
- central air channel
- center: jacket tube for ignition burner

Figure 13: Pillard Rotagas Burner



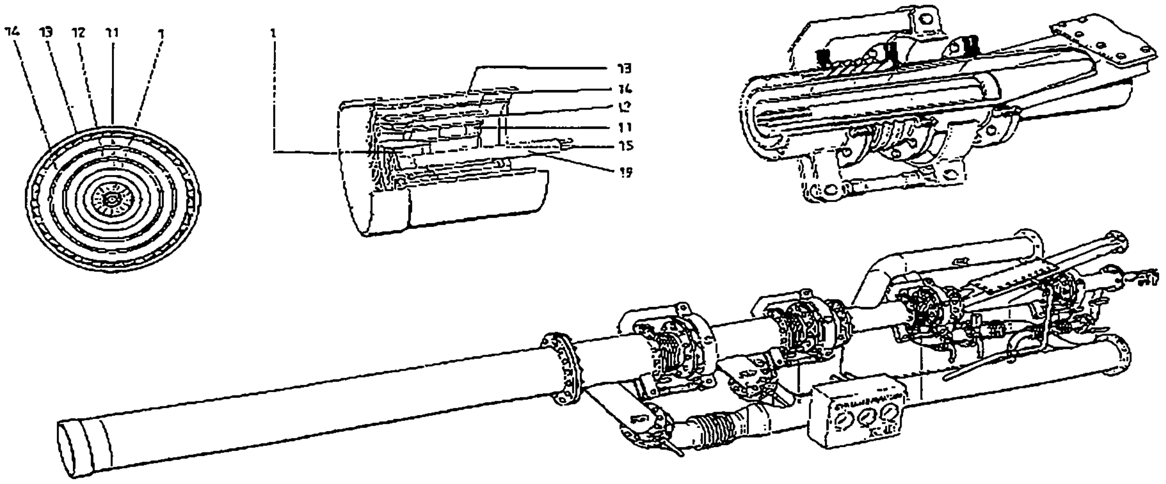
Pillard Rotaflam KGD Gas/Coal/Oil Burner (Fig. 14)

The Rotaflam multipurpose burner is equipped for combined or separate firing of gas, coal and oil. Flame shaping is achieved with separate axial and radial primary air.

Arrangement of the channels (from outside to the center):

- axial air
- radial swirl-air
- single gas channel
- pulverized coal channel
- central air / flame stabilizer
- center: jacket tube with oil atomizing nozzle

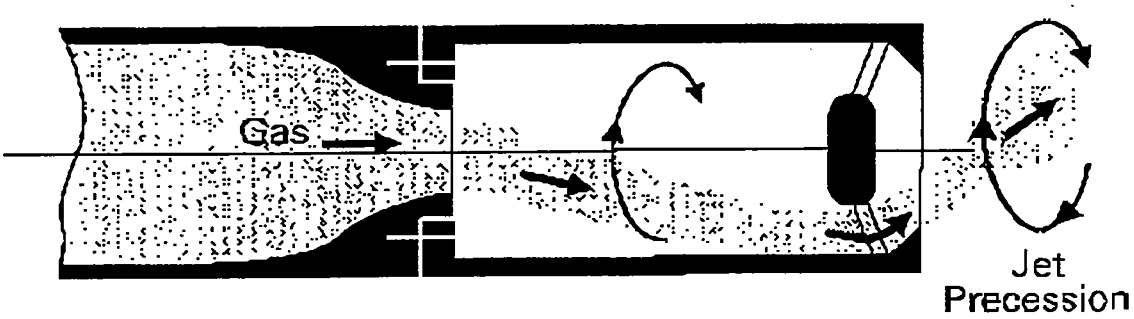
Figure 14: Pillard KGD Gas / Coal / Oil Burner



Gyro-Therm Gas Burner (Fig. 15)

The Gyro-Therm burner applies a special flow phenomena to achieve the air/gas mixing. A "processing jet" is generated in a specifically designed nozzle. Experiences with this burner are limited.

Figure 15: Gyro-Therm Gas Burner



KHD Gas Burner (Fig. 16)

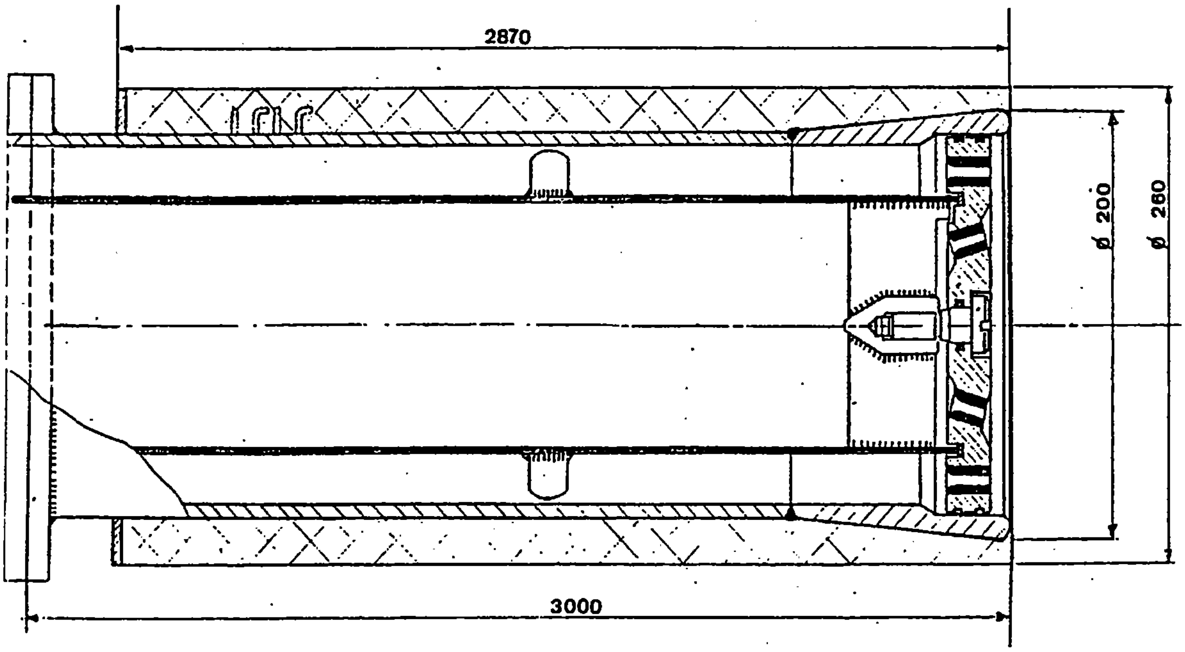
This burner has been used in various kilns since a long time. Owing to the principle on which it operates, it requires a rather high supply pressure (3 - 5 bar) to allow the fuel throughput and the shape of the flame to be varied.

Primary air is not needed for this burner.

Arrangement of the channels (from outside to center):

- axial gas channel
- center: radial gas

Figure 16: KHD Gas Burner



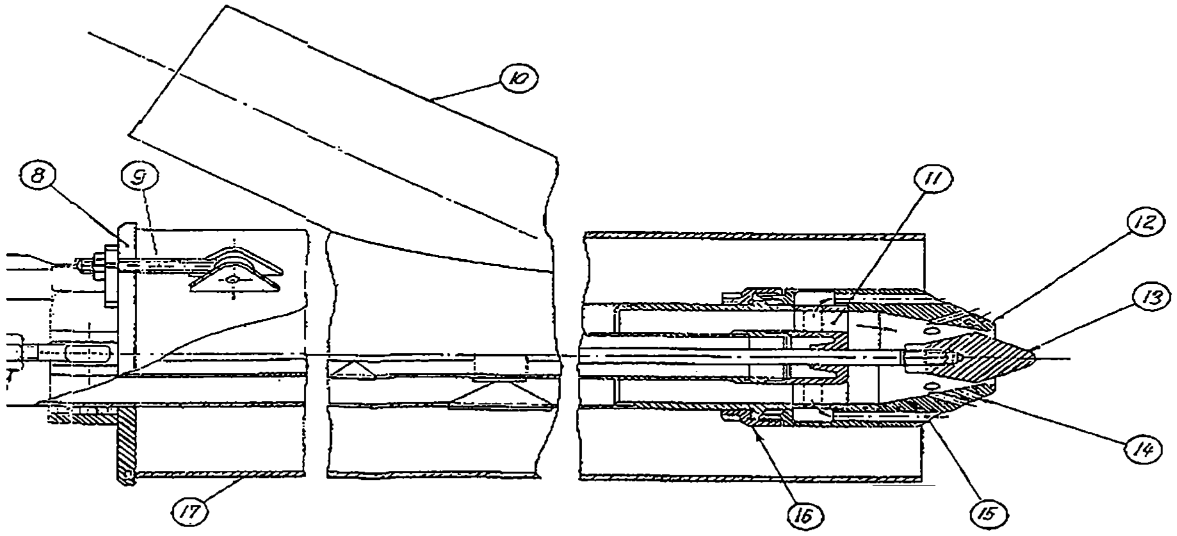
FLS Gas Burner (Fig. 17)

Flame adjustment is done with this burner using the "needle valve method".

Arrangement of the channels (from outside to center):

- primary air (10)
- secondary gas (15)
- primary gas (14)
- center: primary gas with regulating cone (13)

Figure 17: FLS Gas Burner



3. FLAMES

3.1 Prerequisites for the Ideal Flame

The optimization of the burning has to start with the correct adjustment of the flame.

A look at the effects of poor burning makes this immediately clear:

- Unstable coating behavior, particularly in the transition zone, reduces the lining life.
- Incomplete burning and a local reducing atmosphere dramatically increase sulfur volatilization and build-up of coating in the preheater and in the kiln inlet area. Thus a significantly higher dust cycle is created which shifts the entire temperature profile toward the kiln inlet.
- With high CO-formation, secondary combustion forms at the back of the kiln which leads to ring formation.
- As a result, the kiln cannot operate at maximum output, the specific heat consumption increases and the efficiency of the unit drops.

The "ideal" flame can prevent, or at least keep within limits, the operating problems described above. The flame is stable over the entire burn-out distance:

- By continually mixing hot secondary air into the burning zone. Therefore combustion can take place in a controlled manner over the entire flame length.
- No local temperature peaks are formed.
- No local reducing conditions develop over the clinker bed.
- Burn-out is complete at the end of the sinter zone.

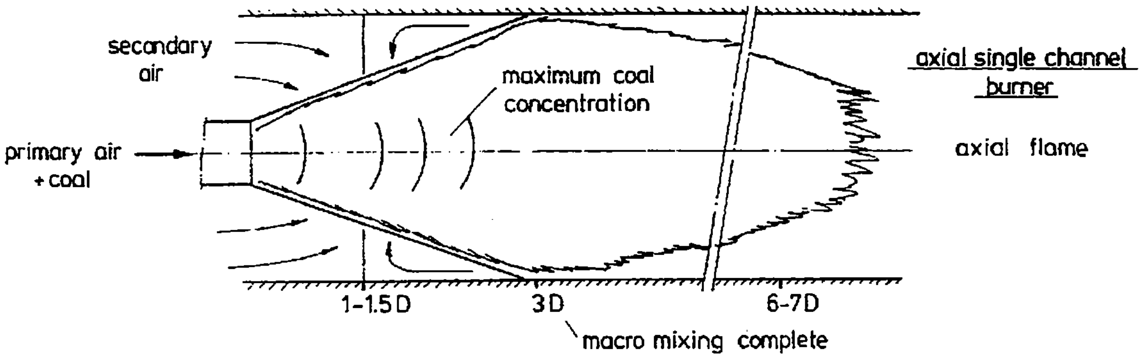
In addition this "ideal flame" has to be achieved with the lowest possible formation of NOx in the exhaust gas.

3.2 Flame Characteristics of the Different Burner Systems

3.2.1 Single Channel Burner

Straight burner pipes tend to produce an axial flame without internal recirculation. The heating up of the fuel jet to ignition temperatures is predominantly by external recirculation of the hot combustion gases (Fig. 18).

Figure 18: Flame Shape of Single Channel Burner



Effects:

- Long sinter zone
- Long retention time of the kiln charge in the hot zone and thus high volatilization of alkalis and sulfur (very suitable for the production of low-alkali clinker)
- High NOx formation

With a constant primary air ratio, the length of the flame reaches a minimum for a given primary air velocity. If the velocity is further increased, the primary air jet develops an excessive suction effect which results in a reverse flow of flue gases. The recirculating flue gas thins the secondary air so much that the flame becomes longer again.

For the recommended range of the specific axial impulsion see chapter 2.1.

However, for optimum flame shaping in response to changing production requirements, burners with adjustable flame (multi channel burners) are to be preferred.

3.2.2 Multi Channel Burner

Multi channel burners can produce a divergent flame with internal and external recirculation zones. The ability to change the relationship between axial and radial air provides an important control mechanism for influencing the flame shape.

A hollow cone flame shape is produced, which can be modified by adjusting the pressure and/or injection-orifice of the radial and axial air (Fig. 19).

The first generation of three channel burners (e.g. Pillard 3-Channel) has some negative effects on the flame shape, if there is a high content of radial air used. Two different flame zones can appear:

- In the first zone with internal recirculation there is intense combustion. Depending on the arrangement of the swirling flow, in this zone coarse fuel particles are spun out of the flame and then burn quickly in the oxygen-rich atmosphere of the hot secondary air.
- In the second, long, instable zone, dominated by external recirculation, burn-out is completed.

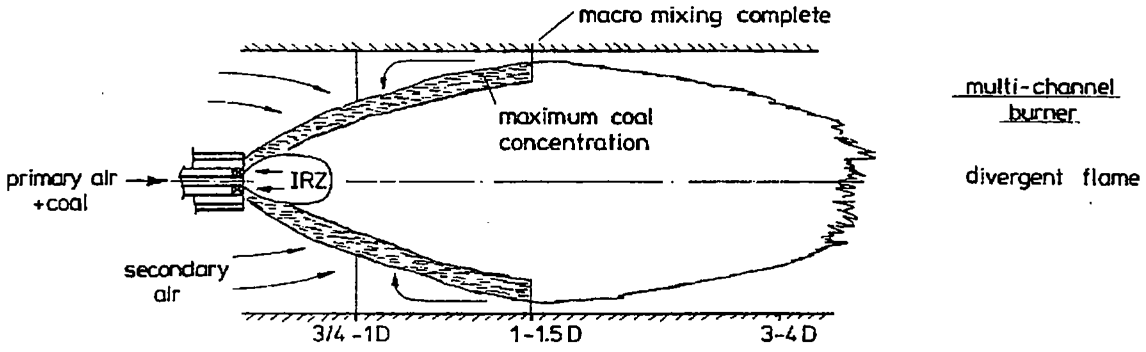
Effects:

- Peak temperatures in the internal recirculation zone.
- With very divergent flames, there are problems with the lining.
- CO formation above the clinker bed caused by incomplete burn-out of the extended fuel jet.
- Unstable coating formation in a long transition zone, caused by an enlarged unsteady burn-out zone.
- Increased NOx formation because of the long retention time of the gasses at high temperatures.
- High sulfur volatilization because of the reducing zone above the clinker bed and the long retention time at relatively high temperatures.

The new generation of three channel burners (e.g. Pillard Rotaflam and KHD Pyrojet - see also chapter 2.2) has been optimized so that these effects are largely avoided. The special arrangement and construction of the primary air channels make the internal recirculation zone (IRZ, Fig. 19) longer and more homogenous. This reduces the length of the burn-out zone with external recirculation. To reduce NOx formation, these burners have been optimized for very low primary air quantities.

For a faster mixing of the primary air with the fuel, these burners have an enlarged flame stabilizer in form of a bluff body in the center.

Figure 19: Flame Shape of New Generation Multi Channel Burner



Effects:

- ♦ Homogeneous temperature distribution, no excessive temperature peaks.
- ♦ Low volatilization rate of alkalis and sulfur.
- ♦ Homogeneous recirculation zone, and therefore low NOx formation.
- ♦ In some cases the flame is too long. Therefore a rearrangement of the coal channel in between the axial and radial air (Pillard Rotaflam) is under discussion.

3.3 Factors Influencing the Flame

In most cases the most favorable operation is achieved with a rather short and powerful flame, giving a high heat transfer rate to the material bed and a short and stable burning zone.

The flame shape may be optimized during operation by adjusting the following parameters:

3.3.1 Primary Air Momentum

A shortening of the flame is normally achieved by increasing the injection momentum of the primary air. With existing burners this can be achieved to a limited extent by increasing the radial air and decreasing axial air correspondingly. With jet burners (KHD) the flame can be optimized by varying number and diameter of jet nozzles and adjusting the jet air pressure.

For burner design recommendations: see chapter 2.2.2.

3.3.2 Position of the Burner in the Kiln

One of the most pronounced influence on flame length is the position of the burner tip: Shifting the burner further in the kiln increases the flame length significantly and vice versa.

This is because the turbulence field of the in-flowing secondary air significantly improves the mixing of the fuel jet with the air. In planetary cooler kilns this effect is less noticeable as the position of the burner tip is defined by the kiln's internal cooling zone.

Recommendations for burner tip position (except planetary cooler):

◆ Dry kiln:	Distance from rotary kiln end to burner tip ≤ 1 m.
◆ Long wet kiln:	Distance rotary kiln end - burner tip approx. 1 m or a little more.

If the burner tip is too close to the rotary kiln end, overheating of the nose ring can occur.

3.3.3 Alignment of the Burner in the Kiln

Basically the burner should be aligned parallel to the kiln axis. In the cold kiln the burner should even be pointed slightly upwards, (specially long burners in kilns with planetary coolers), to compensate for the bending downwards in the hot kiln. If the burner is aligned horizontally (the kiln axis has an angle of approx. 3° to the horizontal) as is often seen, the flame tends to reach the material bed. A local reducing atmosphere is created resulting in high sulfur volatilization.

3.3.4 Secondary Air Temperature

The secondary air temperature defines, firstly, the ignition behavior of the flame (black plume) and, secondly, the possible flame temperature. Insufficient secondary air temperature has to be compensated by fuel, and this means an increase in the combustion gas quantity and a lengthening of the temperature profile. In point of fact, the clinker cooler operation is one of the main factors influencing the flame.

3.3.5 Excess Air

Some excess air is required for complete combustion. The optimum value for excess air to maintain the shortest possible sinter zone is about 10% (equal to 2% O_2 at kiln inlet). Burning at a too low excess air factor increases the burning time and hence the flame length. This creates a reducing atmosphere which increases sulfur volatility thus leading eventually to clogging problems in the preheating zone. If the excess air is significantly higher than the optimum value, the temperature profile is extended again because of a too low flame. This results in an insufficient temperature gradient towards the material bed and a longer sinter zone. For this reason, for example, the secondary firing rate for Air-Through systems is restricted to about 25 ± 5%.

3.3.6 Interaction Flame - Material Bed

As the heat transfer from the flame to the material bed in the sinter zone is almost entirely through radiation, the key factors affecting heat transfer are the temperature and the emissivity of the flame. If radiation is reduced by a dusty kiln atmosphere, a long drawn-out temperature profile with long sinter zone is produced. In this situation, the clinker dust is overheated in the flame and often deposited in the transition zone or even further upstream the kiln in the form of a clinker ring. Ways to counter this effect include all those measures which serve to improve clinker granulation (short and hot flame, different raw mix design).

3.3.7 Burner Dimensions

Basically the burner must be of the right dimensions for nominal operation. This is observed particularly for burners in kilns with precalcination.

Oversized burner nozzles have to be operated with unfavorable primary air settings (either too high primary air content or too low primary air speed) and should be adjusted for nominal operation.

3.3.8 Pulverized Coal Characteristics

- Volatile content:

The combustion time of pulverized coal increases as the volatile content decreases, therefore low volatile coal has a longer burning time and ignition distance than bituminous coal.

- Grinding fineness:

The burning time of a coal dust grain increases approx. with the square of its diameter. The combustion time of a grain of coal increases as its volatile content decreases. Thus, low volatile coal must be ground more finely in order to burn within the desired time, e.g. in order to produce the desired flame length.

Recommendations for optimum grinding fineness:
see paper "Firing Systems - Handling and Preparation of Noble Fuels".

- Ash content:

A high content of ballast material (ash) has a retarding effect on the burning time caused by the reduced coal dust concentration and the lower flame temperatures as a result of the heat absorption of the ballast material.

- Rate of swelling:

The higher the expansion of the coal grain during heating in the flame, the shorter the burning time. Coal types with high density expand / swell less. Therefore petrol coks has to be ground finer to reach the same combustion time as regular coal.

3.3.9 Fuel Oil Flame Adjustments

A faster burn out of the fuel oil can be achieved by lowering the oil viscosity / increasing the oil temperature (recommendations for optimum oil temperature: see paper "Firing Systems - Handling and Preparation of Noble Fuels") or by better atomization (see chapter 2.3).

3.3.10 Natural Gas Flame Adjustments

The main requirement with natural gas burners is the possibility of producing a reverse flow zone in the center of the flame in order to achieve locally a reducing atmosphere where the hydrocarbon molecules agglomerate to larger chains. This is necessary to increase the emissivity of the gas flame, a prerequisite for heat transfer in the sintering zone.

Adjusting the shape of the flame visually is almost impossible, because clearly defined flame contours are hardly recognizable. Optimization of the flame shape should be done following the combustion indicators (see chapter 3.5).

3.3.11 Combined Firing of Different Fuels

When firing two different fuels at the same time, the higher volatile fuel tends to burn more rapidly. this reduces the oxygen content so that the remaining fuel burns further to the back of the kiln.

However, a small amount of high volatile fuel can also have a positive effect on the flame, because it accelerates the ignition and burning of the other fuel.

In extreme cases, two separate burning zones are created. It is therefore important to improve the burning time of the less volatile fuel (e.g. by adjusting the fineness of grinding for coal).

3.3.12 Oxygen Enrichment

By adding oxygen to the combustion air, the flame temperature can be increased significantly. At the same time the specific exhaust gas quantity is lowered. This decreases the energy losses of the exhaust gas and allows to increase the production capacity of the kiln.

Practically feasible is the increase of O_2 in the combustion air by 2 - 3% (from 21% to 24%).

Disadvantages are the higher NOx formation, the lower cooler efficiency for planetary coolers and the oxygen costs.

3.4 Combustion Indicators

One of the main problems in the evaluation of the flame is that, in the rotary kiln, it is only possible to observe the flame visually to a limited extent. On closer consideration, however, there are a number of indicators which can provide much more information about the quality of the flame than can be obtained from simple visual observation.

In the following, the most important operation indicators (combustion indicators) with direct relation to firing parameters are discussed:

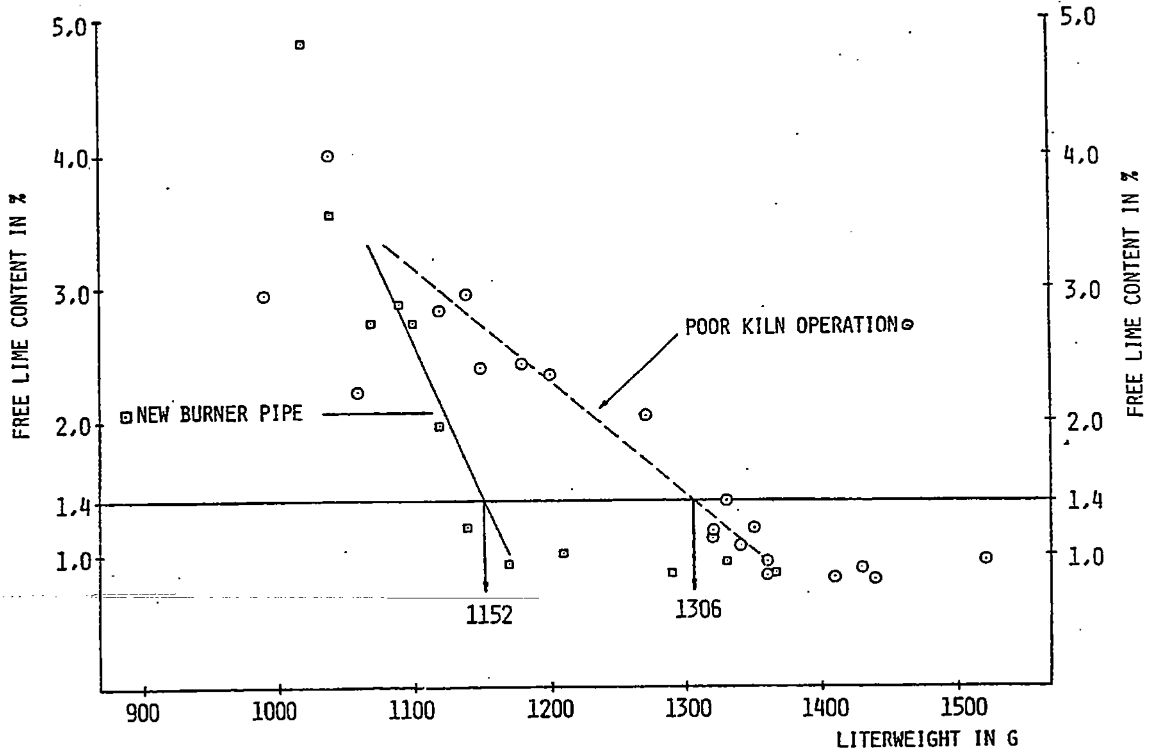
- Clinker quality (free lime, liter weight)
- Burning zone temperature (pyrometer, NOx, amps)
- Coating formation (indicated by kiln shell temperature profile)
- Exhaust gas composition (CO, O_2)
- Kiln inlet temperature
- Volatilization of circulating elements (hot meal analysis, encrustations in the preheater)

3.4.1 Clinker Quality

There exists a close interdependence between sintering zone temperature, granulometry, free lime and literweight of the clinker. The correlation of these parameters is to a high degree influenced by the flame shape. Fig. 20 shows an example, where by flame optimization, the literweight for the required free lime could be lowered. In other words, for the required clinker quality (free lime), burning could be done less hard (liter weight).

Burning less hard leads to substantial savings of energy and refractories.

Figure. 20: **Correlation between Free Lime Content and Literweight with Two Different Operating Conditions**



When modifying the burner settings, the correlation of the parameters shown above has to be closely recorded before and after any change to the burner in order to draw the relevant information for optimum burner settings.

3.4.2 Sintering Zone Temperature

Information about the sintering zone temperature can be obtained by:

- Measuring the clinker bed temperature under the flame using a radiation pyrometer.
- Measuring the NOx concentration in the exhaust gas.
- Measuring the inclination of the kiln charge using a tallumeter.
- Measuring the kiln drive power consumption (Amps or kW) - (only reliable in some cases).

It has to be noted, that all the above mentioned measurements do not supply absolute but rather relative temperature indications and that the NOx-level is also highly depending on the flame characteristics (see chapter 3.6).

3.4.3 Coating Formation

The length of the sinter zone and transition zone gives a guide to the length and temperature profile of the flame. Ring formation can indicate poor combustion, incorrect burner setting, or insufficient fuel preparation (coal not fine enough or poor oil atomizing).

Coating formation can be determined indirectly, by measuring the temperature profile of the kiln shell.

The influence of burner adjustments on coating formation can be checked by recording the kiln shell temperature profile before and after any change to burner settings.

3.4.4 Exhaust Gas Analysis

Exhaust gas analysis at kiln inlet supplies valuable information on the completeness of the combustion. Due to factors such as fluctuations in fuel supply and quality, generally a too high O_2 level would be required for 0% CO. Usually the kiln is set to an O_2 level at kiln inlet, at which < 500 ppm CO is produced. A thus required O_2 level in excess of 2.5% would indicate combustion problems.

Too high CO levels do not only cause energy losses but do also increase Sulfur volatilization and may cause Sulfur rings and cloggings in the cyclones.

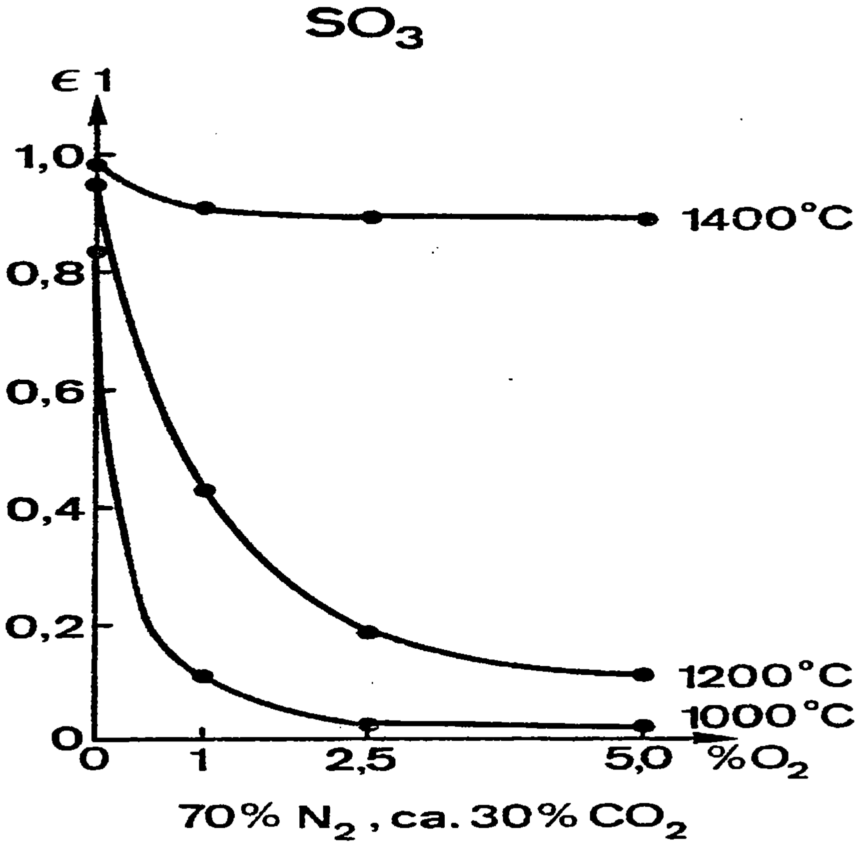
3.4.5 Kiln Inlet Temperature

With preheater kilns, the kiln inlet temperature (= back end temperature) supplies information on flame length and retarded combustion. The target is to have the kiln inlet temperature as low as possible. Kiln inlet temperatures in excess of 1100°C need improvement of the firing system.

3.4.6 Volatilization of Circulating Elements

The flame has an important influence on the volatilization of the circulation elements, especifically on Sulfur. This is governed by factors such as retention time of the material in the hot zone (flame length) and local or general reducing atmosphere including the presence of oversize fuel particles in the material bed (Fig. 21).

Figure 21: **Influence of Temperature and O_2 Concentration on Sulfur Volatility**



To assess the degree of volatilization of the circulating elements, the enrichment of SO_3, Cl and K_2O in the hot meal has to be measured before and after any change to the firing system.

3.5 NOx Formation

NOx formation is dominated as well by peak temperatures as by the amount of air entrained into the primary fuel jet at ignition. NOx reduction measures are deduced essentially from these facts as follows:

- Low primary air ratio
- Flame front near the burner (short ignition distance)
- Flame shaping with the aim to avoid high peak temperatures with at the same time shorter flame
- Lower burning temperatures (free lime, raw mix)

The minimum technically achievable NOx emission with measures related to the rotary kiln burner are in the order of magnitude of 800 to 1'000 mg/Nm^3 (dry basis). Further reduction of NOx requires additional secondary measures such as staged combustion (air / fuel staging, reburning) at the precalciner or NH_3 injection.

For more details on NOx formations see paper "State of Technology of Rotary Kiln Burners".

3.6 Flame Adjustment Procedure

1) Follow the operating instruction of the supplier for a medium flame setting.
2) Wait until kiln is stable before undertaking any adjustment.
3) Progressively adjust parameters (axial/radial air, oil pressure, gas pressure) to get required flame.

- Cautions:
  - axial air outside channel also serves to cool the burner pipe; keep always min.8% of total primary air
  - watch continuously the corresponding combustion indicators
- The kiln reacts slowly to any change. It may take up to a few days to reach stable running conditions again. It is therefore useless to try to adjust a flame within one shift!

4) It is not recommended to operate the kiln with the shortest possible flame. A safety margin for adjustment in both directions should be maintained for control of burning zone disturbance.

NOx Emission: In some countries with severe regulations, the NOx emission might be in a near future the most important parameter for flame adjustment.

4. SECONDARY FIRING / PRECALCINER

The burning conditions for a secondary firing or precalciner burner are quite different from the kiln firing:

- In most cases the combustion takes place in a exhaust gas + air mixture instead of pure air.
- Combustion takes place in a very dusty atmosphere.
- Temperature range of 1000°C instead of 2000°C.

Due to the poor burning conditions, incomplete combustion is quite common in precalciners. Beside CO, coal firing produces carbon skeletons and also CH_4, which both cannot be traced by CO measuring equipment. Further signs for incomplete combustion are:

- Higher gas temperature at bottom cyclone outlet than at precalciner outlet.
- Only moderate drop of the gas temperature over the two lowermost cyclone stages.

Both indication an after-burning within the preheater. This results in increased exhaust gas temperature and heat consumption.

Improvement Measures:

- Avoiding fluctuations of the fuel feed.
- Grinding the coal to the required fineness.
- Providing enough gas retention time in the precalciner. As a rule of thumb for coal firing:
  - gas retention time = 2 to 3 sec.
  - (kiln capacity $[t/d]$) / (precalciner volume inside lining $[m^3]$) $= 7 \pm 2\ t/m^3\ d$

5. LIST OF REFERENCES

1) "Firing Systems"
VA 82/4898/E

2) "Flames and Burners"
VA 93/4056/E

3) "State of Technology of Rotary Kiln Burners"
F. Schneider, PT 96/14078/E

4) W.L. van de Kamp / J.P. Smart
IFRF Research Report CEMFLAM1
"The effect of burner design and operation and fuel type of cement kiln flames"

6. ANNEX

6.1 Formulas and Definitions for the Calculation of Burner Momentum and Swirl Number

6.1.1 Primary Air / Combustion Air:

Kiln heat consumption	Q	[MJ/kgcli]	
Min. combustion air Amin.	0.26 x q	[Nm^3/kgcli]	Good approximation for conventional fuels
Total combustion air A	n x Amin.	[Nm^3/kgcli]	n = excess air factor, n>1
Excess combustion air	Amin. x (n-1)	[Nm^3/kgcli]	
Primary air ratio	Expressed in % Amin.	[%A min.]	

Note:

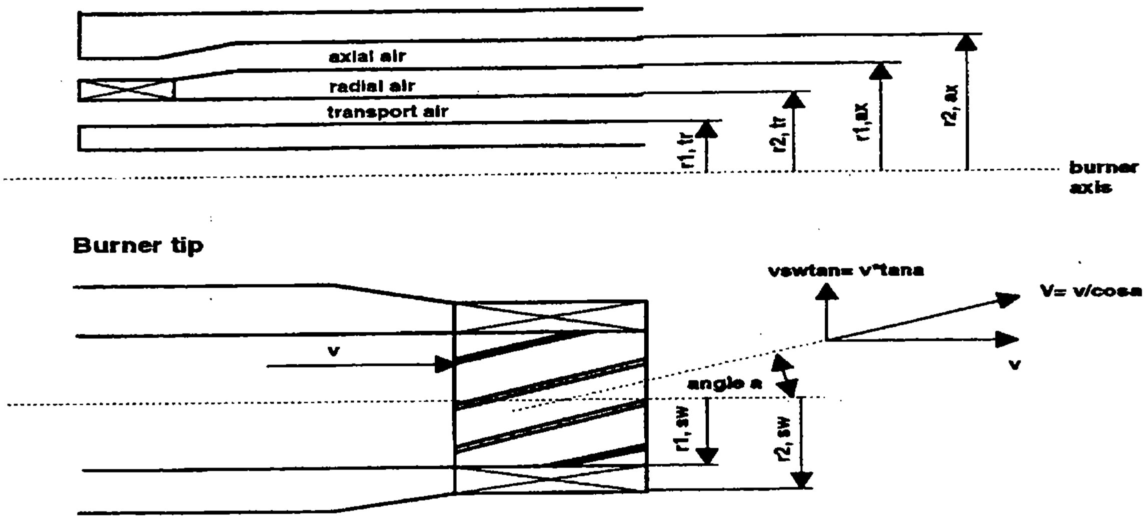
In order to get lower primary air ratio figures, burner suppliers usually relate primary air ratio to total combustion air.

6.1.2 Burner Geometry:

Following burner geometry calculations are based on the list of symbols and units stated below:

$\mathbf{r_i}$	Burner channel radius of channel I	[m]
$\mathbf{r_{eg.\,i}}$	Equivalent channel radius of channel I	[m]
$\mathbf{G_x}$	Axial momentum	[N]
$\mathbf{G_{x.i}}$	Axial momentum of channel I	[N]
$\mathbf{G_{ax}}$	Specific axial momentum	[N/MW]
$\mathbf{G_t}$	Tangential momentum	[N]
$\mathbf{M_i}$	Mass flow through channel I	[kg/s]
$\mathbf{Q_{fuel}}$	Fuel heat input	[MW]
$\mathbf{S_b}$	Burner swirl number	[-]
$\mathbf{v_{i.ax}}$	Axial velocity in channel I	[m/s]
$\mathbf{v_{sw.tan}}$	Tangential velocity on swirling channel	[m/s]

Figure A: Typical Burner Geometry



6.1.3 Mono Channel Burner:

Total specific axial momentum through burner [N/MW]:

$$G_{ax} = \frac{M_{(tr+c)} \times v_{tr}}{Q_{fuel}} \left[\frac{N}{MW}\right]$$

6.1.4 Multi Channel Burner:

Total specific axial momentum through burner [N/MW]:

$$G_{ax} = \frac{\left(M_{sw} \times v_{sw,ax} + M_{(tr+c)} \times v_{tr} + M_{ax} \times v_{ax,ax}\right)}{Q_{fuel}} \left[\frac{N}{MW}\right]$$

Burner Swirl Number:

$$Swirl\,number = \frac{Tangential\,Momentum[N] \times Characteristical\,Swirl\,Radius[m]}{\Sigma(Axial\,Momentum[N] \times Characteristical\,Channel\,Radius[m])}[-]$$

$$S_b = \frac{Gt[N] \times r_{eq.sw}[m]}{\Sigma G_{xi}[N] \times r_{eq.i}[m]}[-]$$

A common method for the calculation of the characteristical or equivalent radius is to determine the radius of gyration for each individual channel cross-section as follows (Mathur and Maccallun - 1967):

$$r_{eq.i} = \frac{2 \times (r_2^3 - r_1^3)}{3 \times (r_2^2 - r_1^2)}[m]$$

For a typical multi channel coal burner with axial-, transport- and swirl air, the burner swirl number can be calculated according to the following formula:

$$S_b = \frac{Msw \times v_{sw,\tan} \times r_{eq.sw}}{M_{ax} \times v_{ax} \times r_{eq.ax} + M_{(tr+c)} \times v_{tr} \times r_{eq.tr} + M_{sw} \times v_{sw} \times r_{eq.sw}}[-]$$